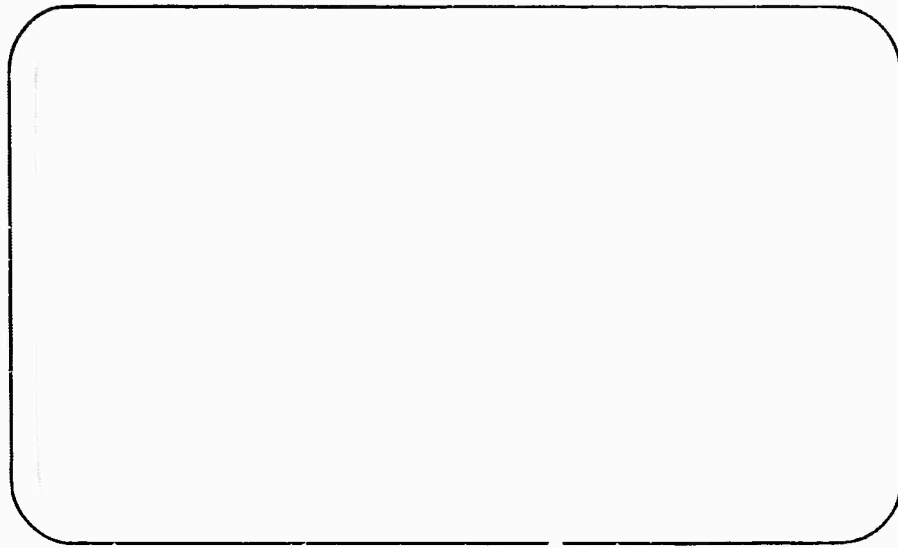


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Westinghouse

ELECTRIC CORPORATION

**First
Semi-Annual
Report**

"THERMAL OPTIC DISTORTION"

Report Period: 16 June 1965 to 16 December 1965

Contract NONr - 4874 (00)

ARPA Order No. 306 Project Code 4730

Prepared for

OFFICE OF NAVAL RESEARCH

Washington, D. C.

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ABSTRACT

This is the semi-annual technical report issued under Navy Contract Nonr-4874(00). The period covered by this report extends from 16 June 1965 to 16 December 1965

The results of preliminary measurements performed on a neodymium doped glass rod previously used on contract Nonr-3922(00) are presented. These experiments include space and time resolved measurements of pump induced birefringence during and after the pump cycle.

Conclusions are drawn from the results of the theoretical and experimental investigations to date, and plans for the next period are presented.

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I. INTRODUCTION

A. SCOPE OF THE PROGRAM AND STATEMENT OF WORK

This semi-annual technical report on Thermal Optic Distortion, Contract Number NOnr-4874(00), reviews the six-month period extending from 16 June 1965 to 16 December 1965. The objective of this program is to conduct a theoretical and experimental research study to determine degradations in optical quality of neodymium-glass laser rods. Inversion measurements, optical path length distribution, birefringence, and thermally induced changes in rod length are to be investigated and appropriate theory developed to explain the observed phenomena.

B. PROGRAM STATUS

During the period covered by this report preliminary measurements were made on a 3/8 x 3 inch neodymium-doped Kodak glass laser rod. This laser rod was one of the laser rods employed on Contract Number NOnr-3922(00) and was pumped in the same laser head used on the above contract. The measurements performed were space and time resolved measurements of pump induced bi-refringence during and after the pump phase.

The theoretical portion of the investigation completed to date covers a preliminary analysis of the pump induced birefringence.

Two clad neodymium doped laser rods, and one undoped glass "control" rod, have been ordered from the American Optical Company. These are scheduled for delivery by 22 December 1965.

Each of the above areas is described separately in the Discussion section of this report.

II. DISCUSSION

A. PUMP INDUCED BIREFRINGENCE MEASUREMENTS

1. Introduction

Initially it is assumed that the degradations in optical quality are purely the result of thermal gradients produced in the Nd doped laser rod during the pump cycle. If this is the case, the distortions observed experimentally should be predictable theoretically if the temperature distribution in the rod is known as a function of space and time during the pump cycle.

To calculate the temperature distribution within the laser rod from knowledge of the pump characteristics only, detailed information on the spectral distribution and intensity distribution of the pump would be necessary. In addition, a detailed knowledge of the quantum-mechanical processes taking place within the laser rod would be required.

In this context it becomes necessary, therefore, to establish an experimental technique whereby the temperature in the rod can be measured as a function of space and time. One technique for determining the temperature distribution, which appears promising at the present time, is to measure the pump induced birefringence and the change in physical length of the laser rod during the pump cycle. From this data the temperature distribution can be calculated provided the induced stress possesses radial symmetry.

2. Theoretical Considerations

Using the thermoelastic stress analysis⁽¹⁾ for an isotropic solid cylinder of radius R and Length L , with a radial temperature distribution $T(r)$, Quell⁽²⁾ has calculated the change in apparent pathlength ΔP for a light wave polarized in either the r or θ directions to be

$$(1) \quad \Delta P_r(r) = L \left\{ \left[n - \alpha_n + \frac{\alpha E}{1-\nu} (2B_{\perp}) \right] T(r) + \frac{\alpha E}{1-\nu} [B_{||} - B_{\perp}] \frac{1}{r^2} \int_0^r T(r) r dr \right. \\ \left. + \left[2\alpha(n-1) - \frac{\alpha E}{1-\nu} (3B_{\perp} + B_{||}) \right] \frac{1}{R^2} \int_0^R T(r) r dr \right\}$$

$$(2) \quad \Delta P_{\theta}(r) = L \left\{ \left[n \alpha_n + \frac{\alpha E}{1-\nu} (B_{||} + B_{\perp}) \right] T(r) + \frac{\alpha E}{1-\nu} [B_{\perp} - B_{||}] \frac{1}{r^2} \int_0^r T(r) r dr \right. \\ \left. + \left[2\alpha (n-1) - \frac{\alpha E}{1-\nu} (3B_{\perp} + B_{||}) \right] \frac{1}{R^2} \int_0^R T(r) r dr \right\}$$

respectively. The symbols are defined as follows:

n = index of refraction at the wave frequency

α_n = thermally induced index change assuming no stress (i. e. , that change produced by uniformly raising the temperature of the entire sample).

α = linear thermal expansion coefficient

E = Young's modulus

ν = Poisson's ratio

$B_{||}$, B_{\perp} = Stress optic coefficients = change in index of refraction per unit stress directed parallel and perpendicular respectively to the direction of polarization.

During the optical pumping cycle of a laser rod, the temperature distribution and hence the path length changes will be a function of time, t . Including the time explicitly, equations (1) and (2) become:

$$(3) \quad \Delta P_r(r, t) = L \left\{ \left[n \alpha_n + \frac{\alpha E}{1-\nu} (2B_{\perp}) \right] T(r, t) + \frac{\alpha E}{1-\nu} [B_{||} - B_{\perp}] \frac{1}{r^2} \int_0^r T(r, t) r dr \right. \\ \left. + \left[2\alpha (n-1) - \frac{\alpha E}{1-\nu} (3B_{\perp} + B_{||}) \right] \frac{1}{R^2} \int_0^R T(r, t) r dr \right\}$$

$$(4) \quad \Delta P_{\theta}(r, t) = L \left\{ \left[n \alpha_n + \frac{\alpha E}{1-\nu} (B_{||} + B_{\perp}) \right] T(r, t) + \frac{\alpha E}{1-\nu} [B_{\perp} - B_{||}] \frac{1}{r^2} \int_0^r T(r, t) r dr \right. \\ \left. + \left[2\alpha (n-1) - \frac{\alpha E}{1-\nu} (3B_{\perp} + B_{||}) \right] \frac{1}{R^2} \int_0^R T(r, t) r dr \right\}$$

In order to determine how accurately equations (3) and (4) describe the path length changes, the temperature distribution $T(r, t)$ must be known. A direct measurement of the temperature as a function of r and t during the pumping cycle does not appear to be feasible. The value of a direct calculation of $T(r, t)$ is also questionable particularly in view of the lack of accurate spectral radiance data for flash lamps. We may however infer $T(r, t)$ from a measurement of the stress optic effects and a measurement of the change in length of the laser rod as a function of time. This may be done as follows. Subtracting equation (4) from (3) yields

$$(5) \quad \Delta P_{r\theta}(r, t) \equiv \Delta P_r(r, t) - \Delta P_\theta(r, t) = B \left\{ T(r, t) - \frac{2}{r^2} \int_0^r T(r, t) r dr \right\}$$

where

$$B \equiv \frac{\alpha E}{1-\nu} [B_{\perp} - B_{\parallel}]$$

After multiplying by r^2 , differentiating with respect to r and rearranging (5) becomes

$$(6) \quad \frac{d}{dr} T(r, t) = \frac{1}{B} \left\{ \frac{d}{dr} [\Delta P_{r\theta}(r, t)] + \frac{2}{r} \Delta P_{r\theta}(r, t) \right\},$$

or

$$(7) \quad T(r, t) = \frac{1}{B} \left\{ \Delta P_{r\theta}(r, t) + 2 \int_0^r \frac{\Delta P_{r\theta}(r, t)}{r} dr \right\} + K$$

Where K is a constant with respect to r only. We know that $T(r, t)$ is everywhere finite and well behaved. Therefore, there exists some δ such that for $0 \leq r \leq \delta$, the temperature may be written as

$$(8) \quad T(r, t) \approx mr + T(0, t)$$

where m is real and finite. Inserting (8) into (5) and taking the limit:

$$(9) \quad \lim_{r \rightarrow 0} \Delta P_{r\theta}(r, t) = \lim_{r \rightarrow 0} B \left\{ mr - \frac{2mr}{3} \right\} = 0.$$

Therefore the stress optic effect on the axis of the rod is zero for all t . From (9) we have for r

$$(10) \quad \Delta P_{r\theta}(r, t) \approx \frac{B}{3} mr.$$

So for $r < \delta$, equation (7) becomes

$$(11) \quad T(r, t) \approx \frac{m}{3} \left\{ r + 2 \int_0^r dr \right\} + K$$

Therefore

$$(12) \quad \lim_{r \rightarrow 0} T(r, t) = K \equiv T(0, t)$$

Then (7) becomes

$$(13) \quad T(r, t) = \frac{1}{B} \left\{ \Delta P_{r\theta}(r, t) + 2 \int_0^r \frac{\Delta P_{r\theta}(r, t)}{r} \right\} + T(0, t)$$

or

$$(14) \quad T(r, t) = \frac{1}{B} F(r, t) + T(0, t)$$

where $F(r, t)$ may be determined by experiment and

$$(15) \quad F(r, t) = \Delta P_{r\theta}(r, t) + 2 \int_0^r \frac{P_{r\theta}(r, t)}{r} dr.$$

We may obtain $T(0, t)$ from a measurement of the change in length of the laser rod as a function of time, $\Delta L(t)$. This change in length is given by⁽³⁾

$$(16) \quad \Delta L(t) = \frac{2 \alpha L}{R^2} \int_0^R T(r, t) r dr.$$

Inserting (14) into (16) yields

$$(17) \quad \Delta L(t) = \alpha L T(0, t) + \frac{2 \alpha L}{BR^2} \int_0^R F(r, t) r dr$$

$$(18) \quad T(0, T) = \frac{\Delta L(t)}{\alpha L} - \frac{2}{BR^2} \int_0^R F(r, t) r dr.$$

After inserting (18) into (14), $T(r, t)$ may be written as

$$(19) \quad T(r, t) = \frac{1}{B} F(r, t) - \frac{2}{BR^2} \int_0^R F(r, t) r dr + \frac{\Delta L(t)}{a L}$$

Since only the difference of equations (3) and (4) have been used in deriving (19), the temperature as calculated from (19) may be used to calculate either $\Delta P_r(r, t)$ or $\Delta P_\theta(r, t)$ and the result checked by direct measurement of either $\Delta P_r(r, t)$ or $\Delta P_\theta(r, t)$. If a successful check is obtained, then $T(r, t)$ as given by (19) will represent a temperature distribution which is consistent with equations (3), (4), and (16). If this desirable state of affairs can be realized, then the output radiation pattern can be calculated with confidence knowing the intensity and polarization of the incident beam.

3. Experimental Procedure

The Kodak laser rod is made from borate glass doped with 3% (by weight) of Nd_2O_3 and has a 60-microsecond fluorescent time constant. It is 3/8 inch in diameter by 3 inches long. The manufacturer's description of this material is found in appendix A. The laser rod is pumped by a 3-inch long helical lamp with an input pump energy of 6500 joules.

The laser rod and the pumping assembly which contained it were placed between two crossed Glan-Laser polarizing prisms as shown in Figure 1. A Spectra-Physics Model 130 He-Ne laser operating at 6328 Å was used as the illuminating source. The light transmitted through the crossed polarizers was focused in the focal plane of a Beckman and Whitley Model 350 Framing Camera to obtain time resolved pictures during the pump pulse, and in the focal plane of an Arriflex 16 mm camera operating at 60 frames per second to obtain time resolved pictures after the pump pulse.

The triggering of the pump source was accomplished by means of the X-Sync output on the Synchro Compur capping shutter. The trigger schematic is shown in Figure 2. With the capping shutter set at 1/400 of a second on X-Sync, the pump was fired 2 milliseconds after the shutter opened. With the shutter remaining open for a total of 3 milliseconds, the Beckman and Whitley high speed camera was able to record the light transmitted through the crossed polarizers for 2 ms prior and 4 ms after the initiation of the pump phase.

Prior to recording the pump induced birefringence, polarizer B was carefully rotated with respect to Polarizer A (Figure 1) to achieve maximum extinction. The light transmitted through the crossed polarizers was then representative of the normal strain present in the laser rod and was photographed for comparison with the pump induced birefringence.

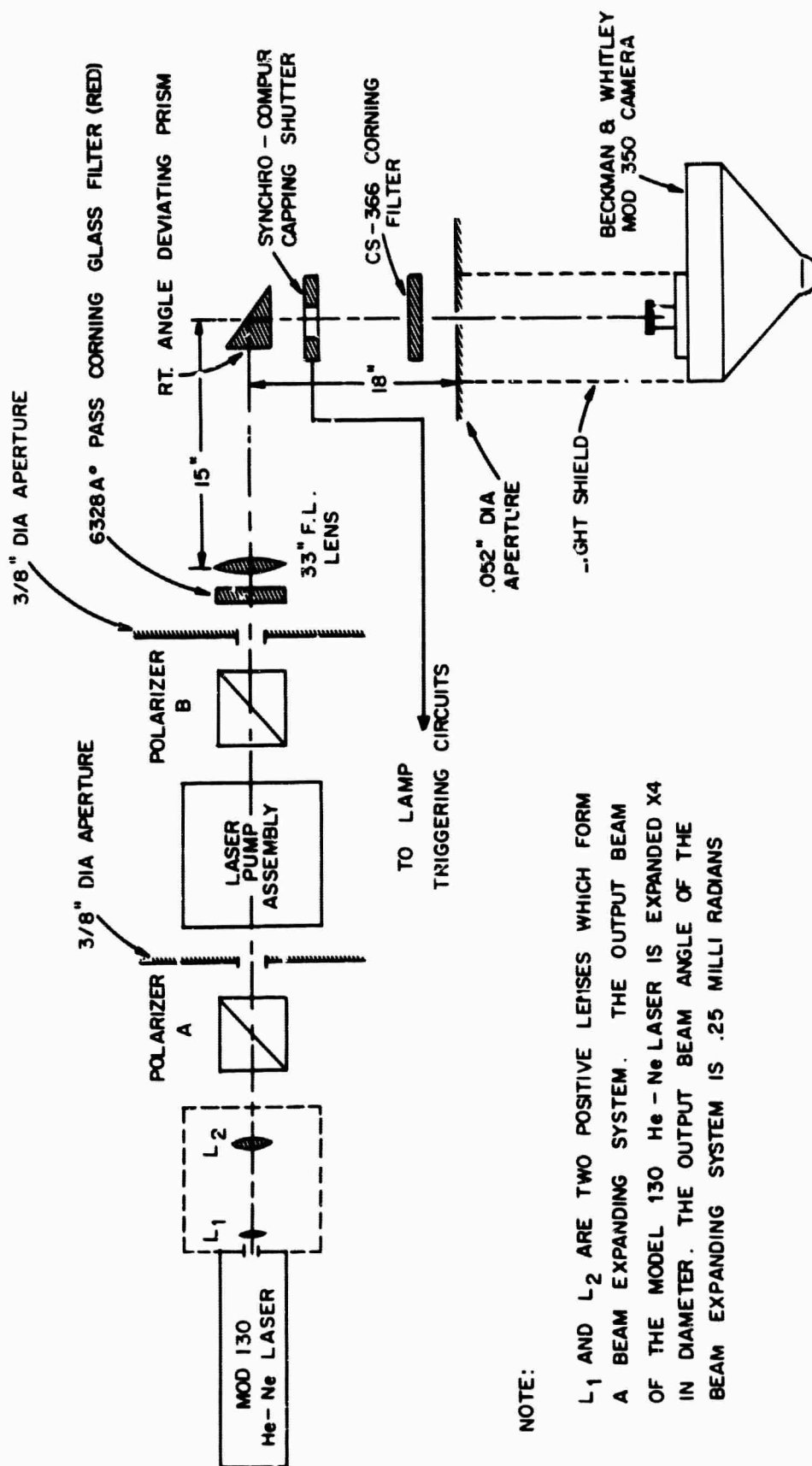


Figure 1. Experimental Diagram for Time Resolved Birefringence Measurements

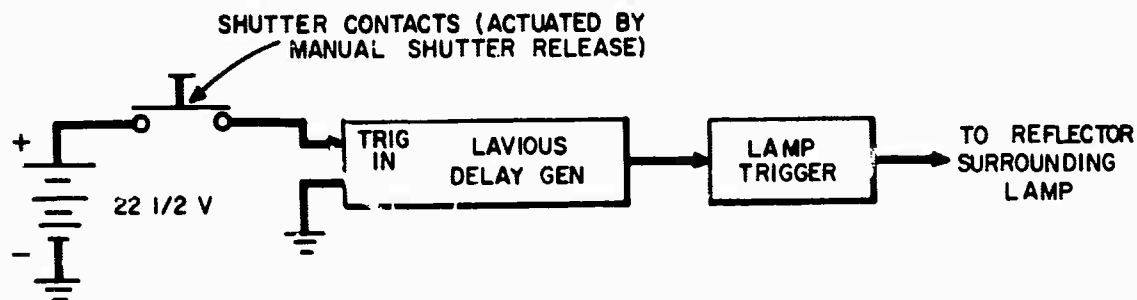


Figure 2. Laser Triggering Schematic

4. Experimental Results

The experimental results obtained from the birefringence measurements can be broken up into three categories: 1) Normal birefringence present in the laser rod at equilibrium room temperature, 2) induced birefringence during the pump cycle; 3) variations in birefringence after the pump pulse due to thermal conduction within the laser rod. Each of these categories will be discussed in the above order.

Figure 3 shows the light pattern transmitted through the crossed polarizers for the laser rod at equilibrium room temperature. Residual strain is quite evident in this photograph but was found to be orders of magnitude lower than that induced by the pump source. No attempt was made at this time to calibrate the film on which the birefringence pictures were recorded since the preliminary investigations were aimed only at determining whether radial symmetry in the temperature distribution existed in the rod during the pump phase.

From Figure 3 it is observed that the residual strain in the rod does not possess radial symmetry. If radial symmetry did in fact exist the pattern observed would take on the form given by ⁴ (see Figure 6-e):



Figure 3. Residual Birefringence in Kodak Neodymium Laser Rod

$$(20) \quad I_t(r, \theta) = \alpha I_i(r, \theta) \sin^2 2\theta \left[1 - \cos \Delta \theta(r, \theta) \right]$$

where $I_t(r, \theta)$ is the light intensity transmitted through the crossed polarizers, α is a constant, $I_i(r, \theta)$ is the light intensity incident on the face of Polarizer A (Figure 1), θ is the angle in cylindrical coordinates, measured counterclockwise from the transmitted polarization axis of Polarizer A, of the vector \vec{r} , $r = |\vec{r}|$, and $\Delta \theta$ is the phase retardation between the radial and tangential polarization components at a point $P(r, \theta)$ on the face of the rod.

Measurements were next made of the pump induced strain during the pump phase. The Beckman and Whitley High Speed Framing Camera was run at 32,900 frames per second. This framing speed resulted in exposure times of 3.3 microseconds with 30.4 microseconds between frames. Figure 4 shows the shape of the white light pump. The input energy to the pump was 6500 joules. Since the capping shutter remained open for 4 milliseconds after the initiation of the pump phase, approximately 130 frames were recorded on film. The film used was Kodak Royal X Pan and was developed to an ASA rating of approximately 3000. Figure 5 shows one of the frames taken during the pump phase; only one frame is illustrated since the birefringence pattern recorded for the 4 milliseconds following the initiation of the

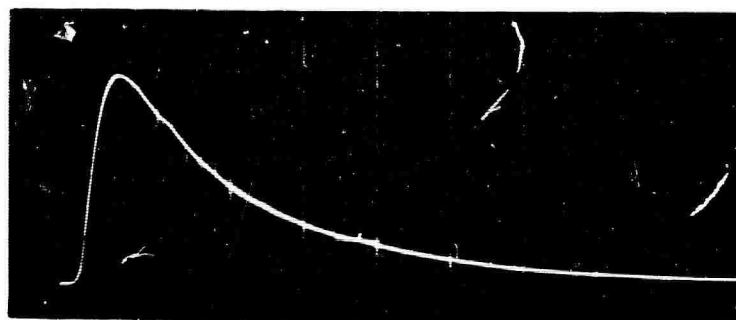


Figure 4. Time Scale: 1 Div = 200 μ S



Figure 5. Laser Rod Birefringence During Pump C, e

pump did not change in shape, only in intensity. From the pictures recorded during the pump phase, the following conclusions can be drawn: 1) The distribution of stress induced by the pump does not appear to possess radial symmetry, 2) during the pump phase and for at least 4 milliseconds after the initiation of the pump the induced strain vectors in the rod do not noticeably change in direction, only in magnitude. The first conclusion is immediately obvious in light of equation (1), the second simply serves to confirm the fact that little thermal conduction takes place within the neodymium rod during the pump phase and for at least 4 milliseconds after it.

The sequence of 16 mm pictures taken at approximately 60 frames per second covered the period from the flash to 16.7 seconds after the flash. At 60 frames per second the time separation between frames is 17 milliseconds. Figure 6 shows a sequence of frames selected from the original film strip to illustrate the important changes in the strain distribution in the rod as they occur. Frame (a) was taken 17 milliseconds after the flash and shows a complete absence of radial symmetry; frame (b) at .26 seconds after the flash shows the strain beginning to radialize; frame (c) at 1.02 seconds after the flash shows essentially radial symmetry of strain with $\Delta \varphi(r, \theta)$ {Eq. 1} differing by at least 2 wavelengths from the center to the edge of the rod; frame (e) at 4.86 seconds after the flash again shows radial symmetry of strain with $\Delta \varphi(r, \theta)$ being less than one wavelength between the rod center and the edge.

By comparing the strain pictures in Figure 5 and 6 it becomes immediately obvious that the high speed pictures taken with the Beckman and Whitley camera suffer from lack of detail. The background of the high speed photographs are also quite grainy due to the high developing speed imposed on the Royal X Pan Film. From these pictures it was concluded that a more intense illuminating source was necessary.

The model 130 He-Ne laser used in these experiments had a .3 milliwatt output. It was decided to obtain a model 112 He-Ne laser from Spectra-Physics which has a single mode output of at least 10 milliwatts. The additional power output of the model 112 will allow high speed pictures to be taken with a significant improvement in detail and contrast.

5. Summary of Results

For the pumping level and geometrical configuration employed in these experiments, radial symmetry of strain was not achieved during the pump phase but occurred approximately 1 second after the pump phase by virtue of thermal conduction within the neodymium rod. In addition, the strain induced by the pump appeared to be at least an order of magnitude greater than the residual stress present in the rod prior to the pump cycle. It was

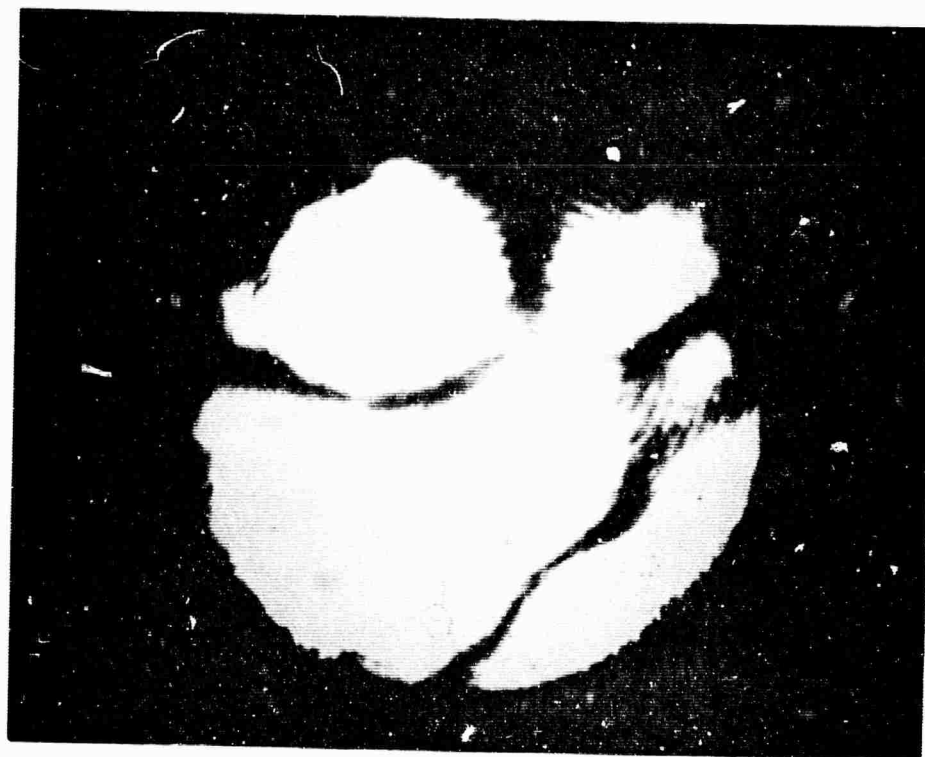


Figure 6a

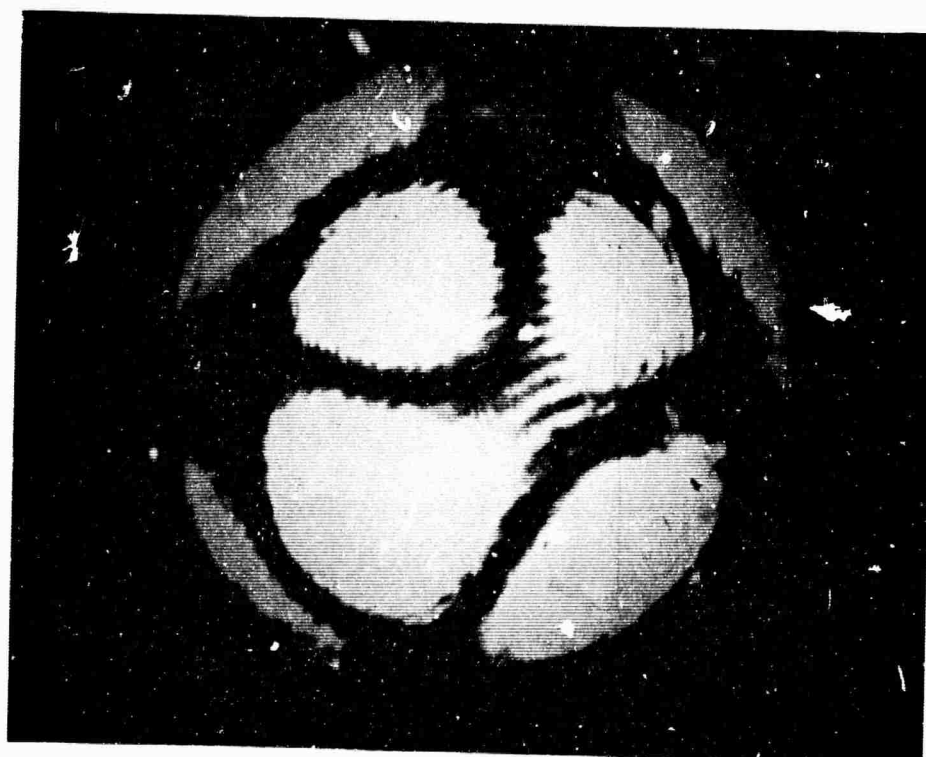


Figure 6b

Figure 6. Birefringence Sequence Taken After Pump Cycle (Sheet 1 of 3)

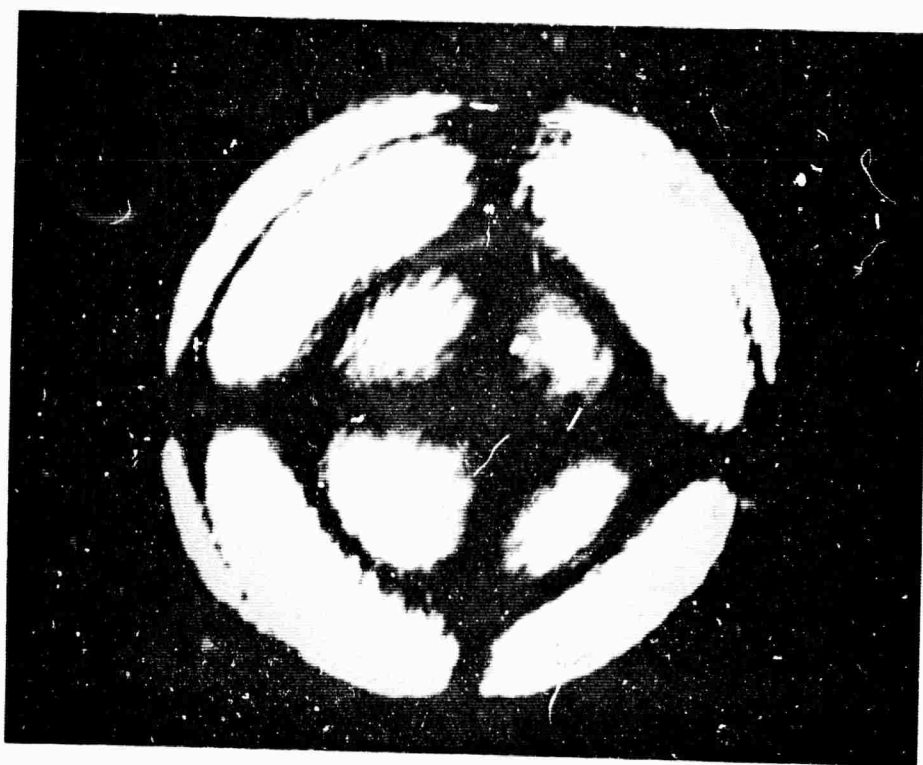


Figure 6c

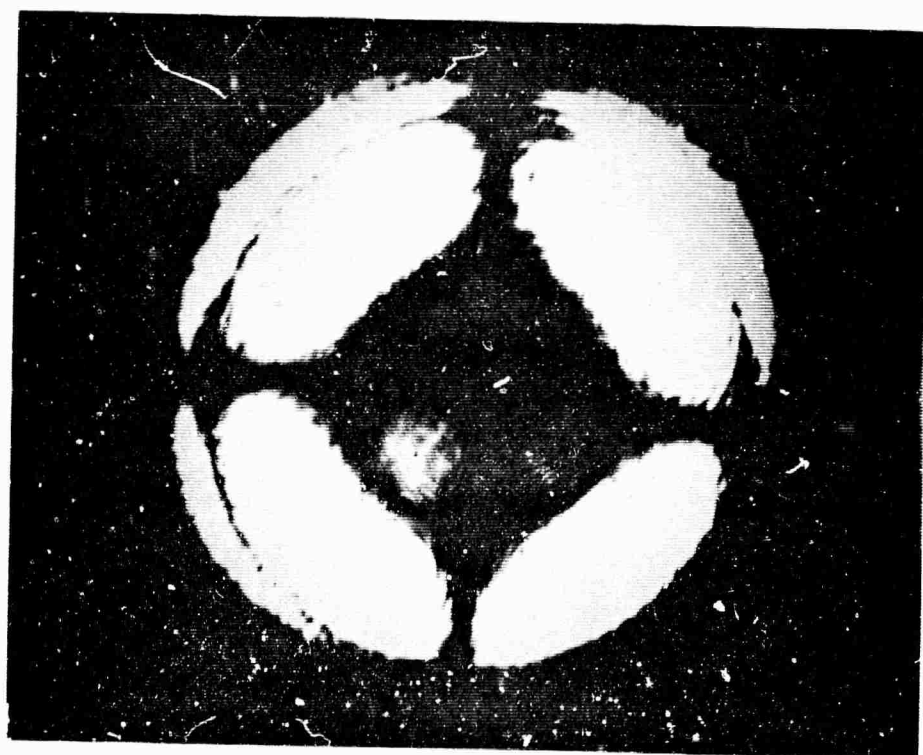


Figure 6d

Figure 6. Birefringence Sequence Taken After Pump Cycle (Sheet 2 of 3)

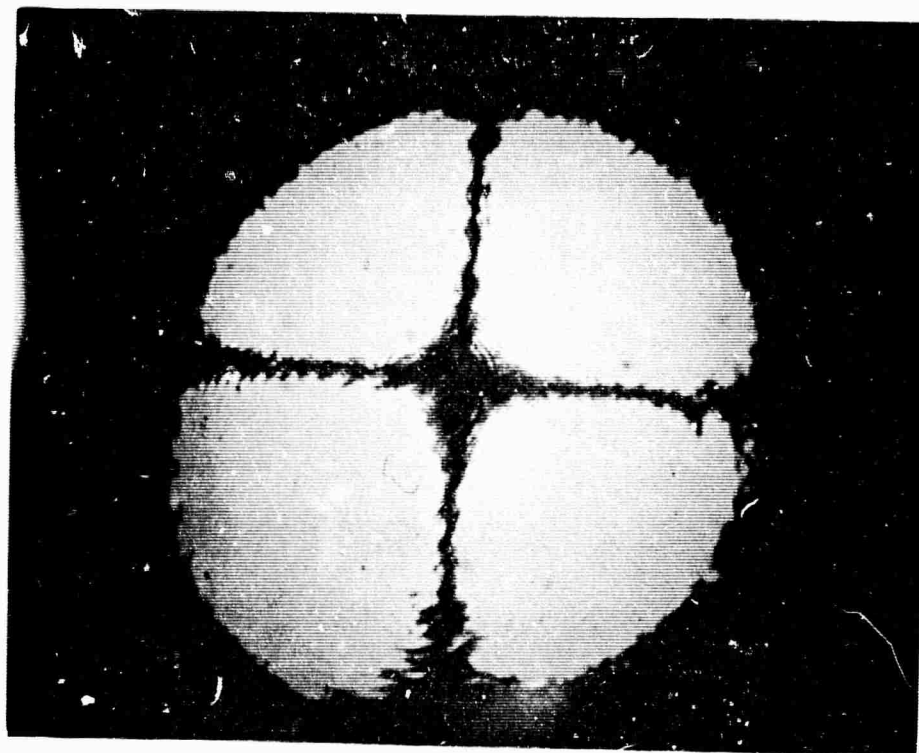


Figure 6e



Figure 6f

Figure 6. Birefringence Sequence Taken After Pump Cycle (Sheet 3 of 3)

also observed that no appreciable conduction of heat occurred in the rod for at least 4 milliseconds after the initiation of the pump cycle.

B. DETERMINATION OF TEMPERATURE BY GAIN MEASUREMENTS

1. Theoretical Considerations

As was stated in section A-1, it appears imperative that the actual temperature in the laser rod as a function of space and time be known if one is to construct an adequate theoretical model to explain the optical distortions which occur in a neodymium doped rod. Consideration was given to the possibility of determining the temperature distribution in the laser rod by performing time resolved gain measurements. After careful study, it was concluded that this technique presented difficulties well beyond the scope of the present program.

Consider a typical energy level diagram for a neodymium doped glass as shown in Figure 7⁵. Heating of the neodymium doped rod occurs primarily by three processes:

1) Absorption of pump radiation directly into the glass host, 2) phonon transitions within the pump band, terminating of the $4F_{3/2}$ level; 3) phonon transitions between the $4I_{13/2}$, $4I_{15/2}$ states to the $4I_{9/2}$ ground state.

To prevent solarization of the neodymium doped rod a pyrex sheath usually surrounds the rod. This sheath absorbs the majority of pump radiation below 2800Å and above 3.3 microns so that direct heating of the rod via the glass host can normally be neglected. The relative intensities or fluorescent efficiencies for the .88, 1.06, and 1.35 micron lines can be determined, so that by knowing the population of the $4F_{3/2}$ state as a function of space and time the temperature contribution from the $4I_{13/2} \rightarrow 4I_{9/2}$ and $4I_{15/2} \rightarrow 4I_{9/2}$ transitions can be calculated. When one further considers the phonon transitions which occur between the discrete pump band levels that terminate at the $4F_{3/2}$ state it becomes immediately obvious that a detailed knowledge of the spectral distribution of the pump radiation be known at each spatial point and during each time increment.

For the particular pumping scheme and laser rod used for making the measurements discussed in Section A, the absence of radial symmetry in the strain pattern during the pump cycle indicated either a nonuniformity in pump energy falling on the laser rod or localized distortions in the laser rod itself or a combination of both effects. Regardless of the cause of the non-radial strain distribution, a detailed knowledge of the spectral distribution and intensity of the pump inside the rod would be required to theoretically calculate the

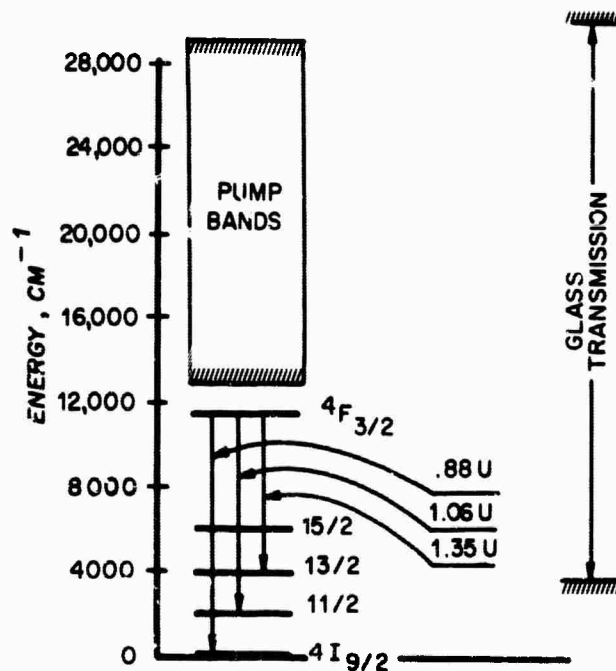


Figure 7. Energy Level Diagram for Nd^{+3} in a Barium Crown Glass Base

temperature distribution. Obtaining this information when a non-symmetric temperature distribution is observed is extremely difficult and beyond the scope of this contract.

If a pumping scheme can be realized where the strain and hence the temperature distribution has radial symmetry, it can be assumed that the pump power density incident on the surface of the laser rod is uniform⁶. With this assumption and a knowledge of the spectral and temporal output of the pump source, obtained by taking time resolved spectra of the pump source, the temperature distribution within the laser rod can be calculated theoretically. The calculated temperature can then be compared with that obtained from the induced birefringence measurements to see if correlation exists. Calculation of temperature from knowledge of the pump characteristics does not require an a-priori knowledge of the gain distribution within the rod once a radially symmetric temperature distribution is obtained.

2. Summary

The temperature distribution in a neodymium doped glass laser rod cannot in general be calculated from the gain alone but requires additional knowledge about the spectral and

temporal variation of the pump source at each point in the rod. The latter quantity is extremely difficult, if not impossible, to obtain when the temperature distribution is anything but radially symmetric within the laser rod. For radially symmetric temperature distributions a knowledge of the gain is not required to calculate the temperature. It would appear; therefore, that gain measurements are not required to establish temperature but can be used, only if radially symmetric temperature distributions are realized, primarily to establish correlation between the calculated temperatures and predicted performance characteristics of the laser rod.

III. FUTURE PLANS

A. GENERAL

Since the preliminary measurements of induced temperature distribution performed on the laser rod-pump cavity combination employed previously on contract NOnr-3922(00) showed no radial symmetry, it is apparent that a method must be devised that has a maximum probability of achieving radial temperature distributions.

B. LASER RODS

Consider first the Kodak neodymium doped rod used previously on contract NOnr-3922(00). This rod has a frosted outer surface which can affect the internal temperature distribution by means of diffuse reflection of amplified transverse 1.06 micron spontaneous emission from the outside walls of the rod. In addition, the Stress-Optic coefficients necessary to calculate temperature distribution from birefringence measurements are not known. In order to assess the relative effects on optical distortion caused by the glass host and doping concentration it is necessary to have a rod made from the undoped glass host. An undoped rod was not ordered with the original Kodak laser rod.

To eliminate these difficulties, two clad AOLux Nd doped laser rods measuring 1/2 x 3 inches along with an undoped glass host "control rod" were ordered from the American Optical Company. The manufacturer's specifications for these laser rods is given in Appendix B. The 1.06 micron absorbent index-matched cladding is quite effective in preventing build-up of energy in whispering modes, thus preventing energy losses by suppressing amplified spontaneous emission. Furthermore, the cladding acts to increase the pump energy falling on the active core while also providing a more even distribution of pump energy within the rod than could be achieved with an unclad rod⁷.

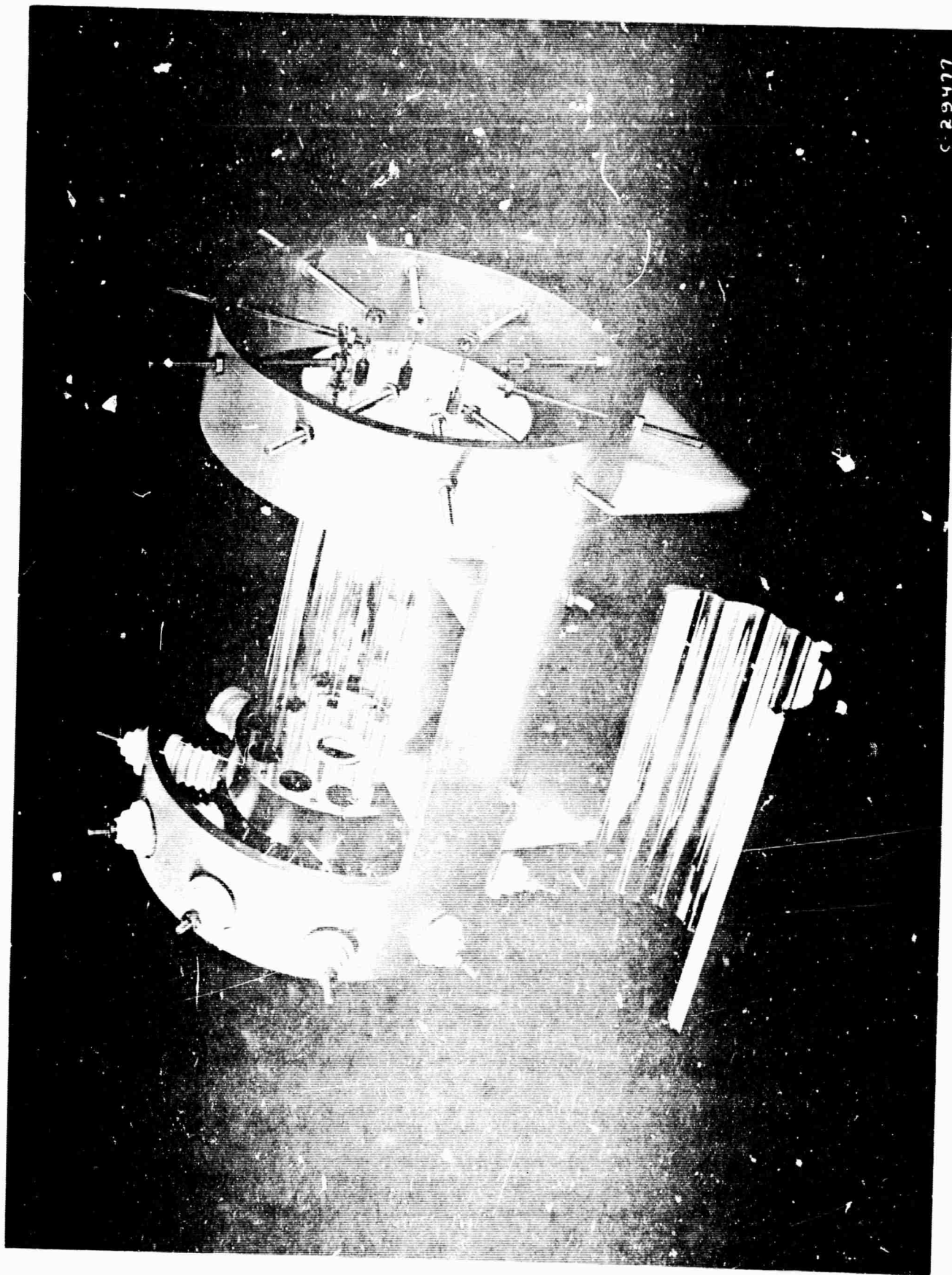
C. PUMP CAVITY

Construction of a pump cavity has begun which should insure a uniform distribution of pump energy over the surface of the clad laser rod. This cavity has been constructed so that the uniform pump intensity is the result of spatial integration of the pump light within the cavity. Due to the unpredictable intensity distribution in the discharge of high intensity pump lamps, it was felt that use of spatial integrating techniques was the only way to achieve uniform pumping, thus eliminating any dependence on the detailed discharge characteristics of the pump lamps.

To conserve time and money, one of the presently available laser heads is being modified. In addition, the basic head design which is being modified lends itself quite well to spatial integration techniques. Figure 8 illustrates the laser head to be used prior to the modifications. The laser head illustrated utilizes ten linear 8 inch arc length lamps; each lamp being pumped by a shaped, 600 microsecond long pulse with an energy content of up to 2000 joules. For the modified head design, the silvered reflector illustrated will be replaced with an MgO reflector. The MgO will be packed between two concentric glass cylinders, the thickness of the MgO being .4 inches. The inside diameter of the reflector will be 4.5 inches with diametrically opposite flash lamps having a center separation of approximately 3.5 inches. The separation of the ends of the pump cavity will be 7 inches minimum. Surrounding the laser rod will be a Pyrex sheath with an inside diameter of 1.9 inches. This sheath will have a ground outside surface to diffuse the direct radiation from the pump lamps. Although the efficiency of this type of cavity is quite low, the design should result in quite uniform pumping along the length of the laser rod. In addition, the 20,000 joule capability of the laser head should still result in a reasonably high gains being obtained in the clad laser rod.

D. EXPERIMENTAL PROCEDURE

With the completion of the modified ten lamp laser head the first measurements to be made on a clad laser rod will be directed toward determining the temperature distribution in the clad rod. This will be accomplished by means of the previously described technique for measuring the induced birefringence. Once radial symmetry in the temperature distribution has been verified, detailed measurements of the phase shift at each point $[P(r, \theta)]$ on the end surface of the rod will be made. The next step will be to totally silver the ends of the laser rod, and by interferometric techniques to measure the physical change in length of the



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Figure 8. Unmodified Laser Pump Cavity

rod at each $P(r, \theta)$ and during each time increment Δt . From these two measurements the temperature distribution in the laser rod can be calculated as a function of space and time. If this calculated temperature distribution is correct the change in optical path length through the laser rod is readily calculable. The next experiment to be performed will then be to measure by interferometric techniques the actual optical path length variations and to correlate these results with the predicted effects. For correlation to exist between the measured and calculated optical path length variations implies that the temperature distribution originally determined is correct.

If radial symmetry of strain is achieved and time permits the spectral and temporal output of the flash lamps will be measured. From this information a two dimensional or three dimensional^{8, 9, 10} model can be used to calculate the temperature distribution expected in the laser rod assuming bleaching effects are negligible. Correlation being achieved here between the calculated and measured temperature will verify the validity of the particular model used to calculate the expected temperature distribution.

Additional measurements of time resolved gain and loss across the face of the rod will allow determination of the population of the $4F_{3/2}$ level. This information in conjunction with the spectral distribution of the pump within the rod, calculated from the model verified previously, should provide the final correlation necessary to construct a mathematical model of the principle quantum mechanical processes and optical distortions which are induced by the pump source.

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APPENDIX A

PROPERTIES OF EASTMAN KODAK COMPANY
NEODYMIUM GLASS LASER RODS

APPENDIX A

PROPERTIES OF EASTMAN KODAK COMPANY

NEODYMIUM GLASS LASER RODS

A. MATERIAL IDENTIFICATION: Kodak Laser Glass, Type ND-10

B. OPTICAL PROPERTIES:

- | | |
|------------------------|---|
| 1. Glass | Eastman Kodak Rare Earth Optical Glass |
| 2. Doping | 1% and 3% by weight of neodymium oxide |
| 3. Emission Wavelength | 1.06 microns, ± 0.01 micron |
| 4. Line Width | approximately 150 Angstroms |
| 5. Absorption | see attached curve, Figure B-1 |
| 6. Index of Refraction | $N_D = 1.6670$ with 1% doping (ranges as high as 1.7030, depending on the concentration of neodymium) |

$$n_F - n_C \quad .01241$$

$$n_D - n_{A'} \quad .00803$$

$$n_e - n_C \quad .00675$$

$$n_F - n_D \quad .00874$$

$$n_g - n_F \quad .00673$$

$$n_h - n_g \quad .00559$$

7. Index Variation vs. Temperature*

$^{\circ}\text{C}$	$\Delta N_D (X10^{-5})$	$^{\circ}\text{C}$	$\Delta N_D (X10^{-5})$
100	11.8	-60	+1.2
80	8.0	-80	+3.0
60	5.0	-100	+5.2
40	2.7	-120	+7.5
20	1.1	-145	+10.5
0	0.0	-170	+13.3
-20	-0.5	-194	+15.7
-40	0.0		

*F. A. Molvy, JOSA, Vol. 39, NO. 7, July 1949

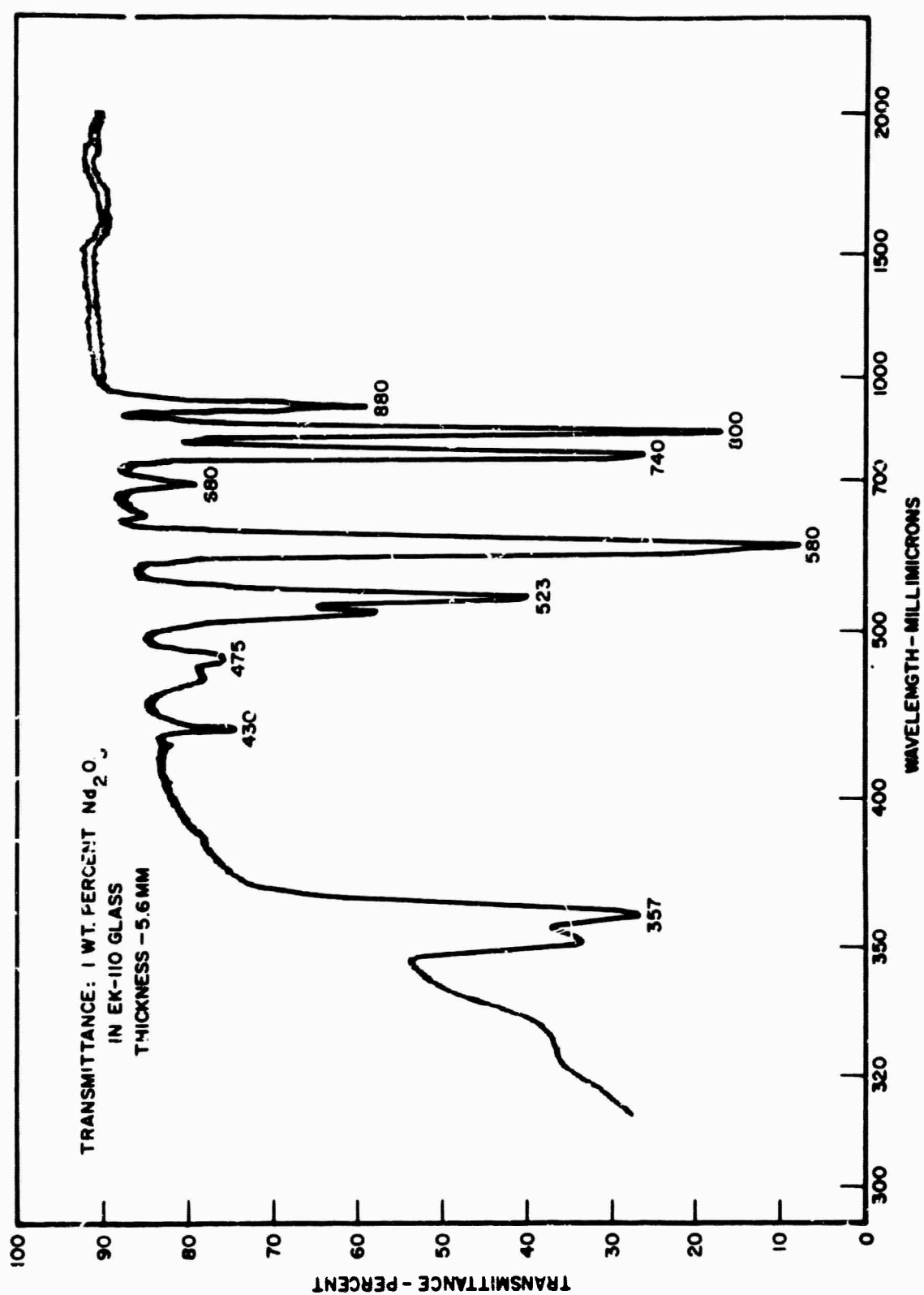


Figure A-1. Absorption Spectra of Kodak ND-10 Laser Glass

C. PHYSICAL PROPERTIES

- | | |
|---|--|
| 1. Specific Gravity | 4.1 gm/cc |
| 2. Coefficient of Expansion | (25°C - 125°C) 6.4×10^{-6} |
| 3. Water Solubility | Stains slightly after 8 hours in standard humidor test (100°F, 90% r.h.) |
| 4. Acid Solubility | Berger Class 5 |
| 5. Littleton Softening Point
($10^{7.6}$ Poise) | 701°C |
| 6. Littleton Anneal Point
($10^{13.0}$ Poise) | 628°C |
| 7. Littleton Strain Point
($10^{14.5}$ Poise) | 610°C |
| 8. Thermal Shock | Rods have been immersed from ambient room temperature into liquid nitrogen. After temperature stabilization, the same rods have been returned to ambient room temperature. No apparent damage has been observed. |
| 9. Thermal Conductivity (i% doping) | |

Temperature

Thermal Conductivity (Cal

52°C	.0019
69°C	.0021
91°C	.0021
114°C	.0022
138°C	.0023
164°C	.0023
196°C	.0024

10. Modulus of Rupture (1% doping)

<u>Temperature</u>	<u>Modulus of Rupture (psi)</u>
25 °C	17,600
100 °C	20,500
250 °C	18,200

11. Modulus of Elasticity (1% doping)

<u>Temperature</u>	<u>Modulus of Elasticity (psi x 10⁶)</u>
25 °C	14.4
100 °C	15.0
250 °C	16.6

D. END SURFACE COATINGS

1. Either dielectric coatings or anti-reflection coatings can be supplied. Dielectric coatings are optimized for performance at 1.07 microns. Because of the low loss coefficient of this glass, special low-absorption dielectric coatings are required. Silver coatings are not recommended.

2. Standard anti-reflection coatings should be applied to rods intended for use with external mirrors.

E. LASER PERFORMANCE

- | | |
|-------------------------------|---|
| 1. Loss Coefficient | 0.16%/cm |
| 2. Efficiency | 0.5 to 2.5%, dependent on rod and flash tube geometry and coupling. |
| 3. Threshold | Threshold is dependent upon many variables, and specific values cannot be stated. Type ND-10 Glass is characterized by low threshold. Figures ranging around 4 joules have been reported. |
| 4. Power Output | Greater than 1 joule per cubic centimeter of glass. |
| 5. Fluorescence Time Constant | Type ND-10 Glass has a fluorescence life-time of about 60 microseconds. |

Output divergence from a Type ND-10 rod, 2" long x 1/4" diameter, has been measured at less than 2 milliradians. This can be reduced with remote external mirrors or external mode selection.

Cooling may be desirable to maintain ambient conditions at high repetition rates. However, the fluorescence transition responsible for laser action terminates well above ground state, and this laser glass does not require refrigeration for its operation.

1. Sizes

Kodak laser rods, finished, are available in sizes up to 3/4" diameter x 30" long.

2. Configurations

- a. Rods can be supplied with flat ends, spherical ends, chisel-tipped internally-reflecting ends, Brewster's angle, or any combination of these.
- b. They are not presently offering clad rods of this material.

3. Standard Size Tolerances

- | | |
|-------------|------------------|
| a. Diameter | + .000", - .005" |
| b. Length | + .000", - .020" |

4. Finish Tolerances

- a. End flatness held to 0.1 wave.
- b. End parallelism held to 6 seconds of arc.
- c. The cylindrical surface is normally finished to an optical shine, but can be supplied with a more precise optical polish, or fine ground, on a custom basis.

5. Laser . d Testing

- a. Every finished laser rod will be optically tested, using a Twyman-Green interferometer with a gas laser source, checking optical homogeneity of the material as well as end flatness and parallelism. With multi-layer dielectric end coatings, this can be done after the rod is coated and at any time during its useful life.
- b. Every finished rod will be lased before shipment, but with no guarantee on the nature of its performance, since there is so much variation between optical heads and pump systems.

6. Delivery

- a. Certain smaller rods will be stocked for immediate delivery.
- b. Special orders and custom configurations can usually be shipped in 30 to 60 days. If a special glass melt is necessary, delivery will be 60 to 90 days.

(All of the above material is from specifications supplied by Eastman Kodak Company.)

APPENDIX B

PROPERTIES OF AMERICAN OPTICAL AOLUX
NEODYMIUM GLASS LASER RODS

Solid and Clad AOlux Laser Rods

<u>Flatness</u>	1/10 wave at 1.06 microns
<u>Perpendicularity</u>	90° ±2 min. to rod axis
<u>Parallelism</u>	10 sec. arc (up to 1/4" diameter) 6 sec. arc (over 1/4" diameter)
<u>Brewster Angle</u> ($\theta_E = 56^\circ 30'$)	$\theta_B \pm 30$ min. arc
<u>Parallelism between Brewster faces</u>	8 min. arc to axis 15 min. to normals
<u>Roof ends centering</u>	±.003" (under 1/4" diameter) ±.005" (1/4" diameter) ±.008" (over 1/4" diameter)

Material Nom. 5 wt. % Nd₂O₃ in barium crown optical glass
 $n_D = 1.519$ $V = 58.6$
 $n_{1.06} = 1.509$

Physical Properties Strain point = 450°C
 Linear Expansion Coeff. (50-300°C.) = $10.3 \times 10^{-6}/^\circ\text{C}$
 Density = 2.63 gm/cm³
 Water Solubility 0.053 microns (powder test)
 Thermal Conductivity = .002 cal/sec/cm/°C.
 Number Nd ions/cc = 4.6×10^{20}

Laser Properties Wavelength = 1.06 microns
 Fluorescent line width: at 1.06 microns = 180Å at 77°K.
 at half width = 250Å at 300°K.
 Lifetime = 0.57 milliseconds
 Specific gain/cm/joule stored/cm³ = .08

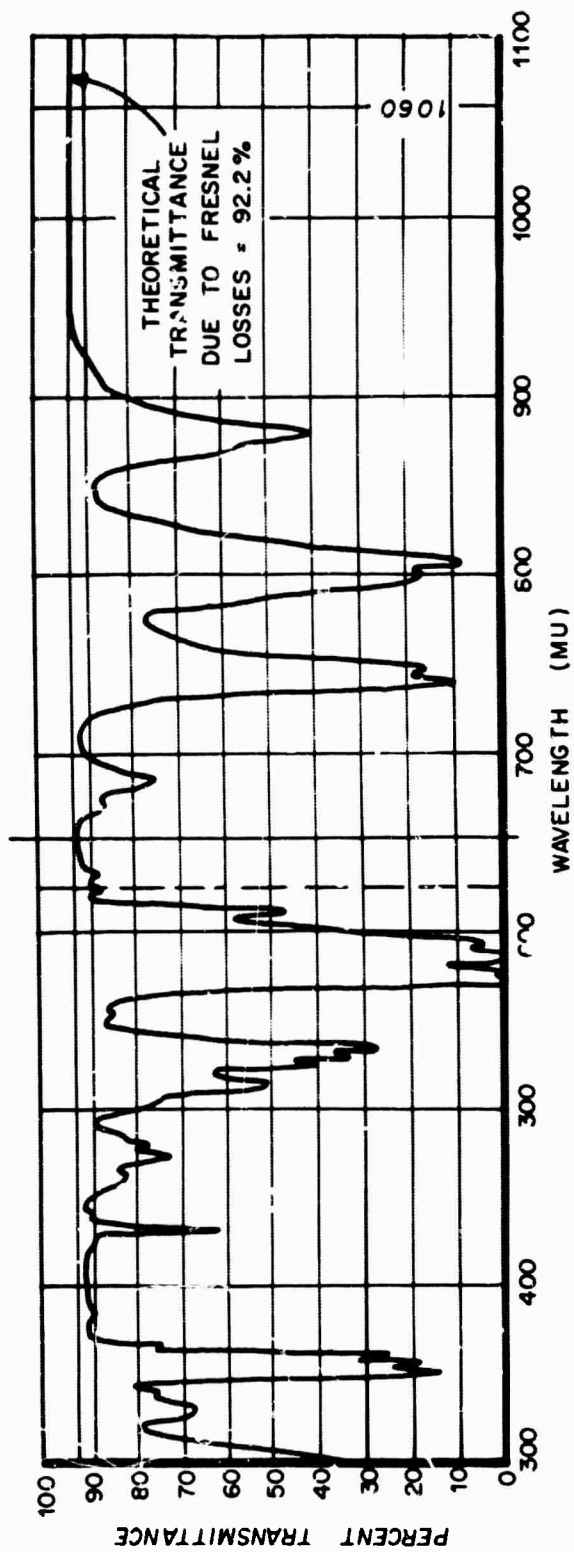


Figure B-1. Absorption Spectrum of AOLux

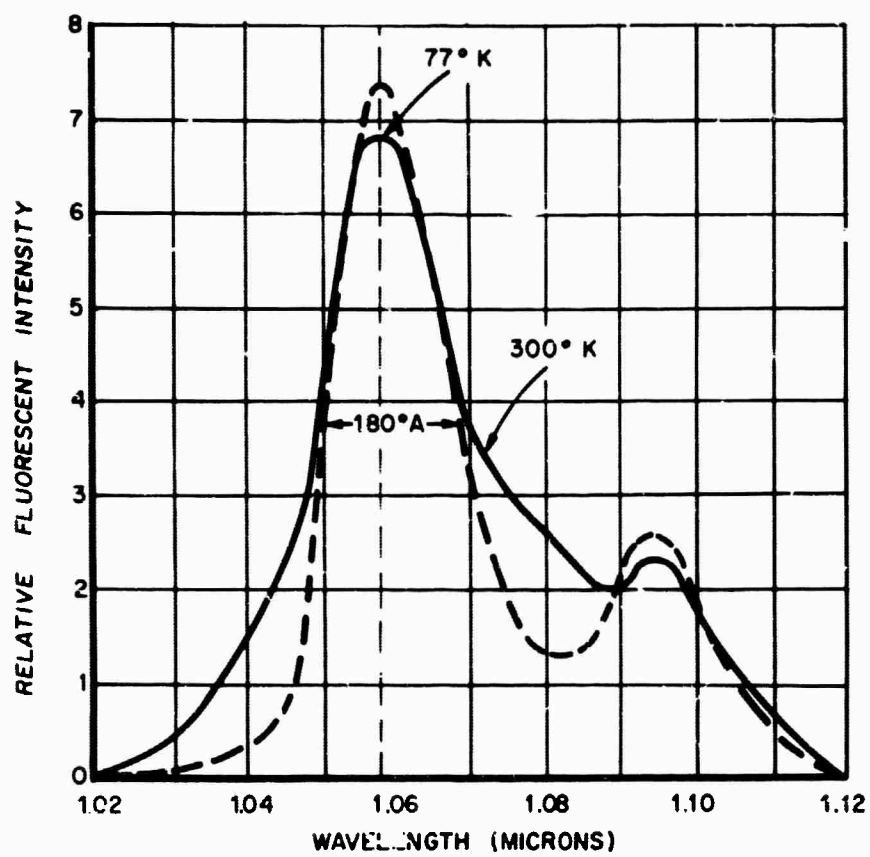


Figure B-2. Fluorescence of AOLux (5% Nd₂O₃)

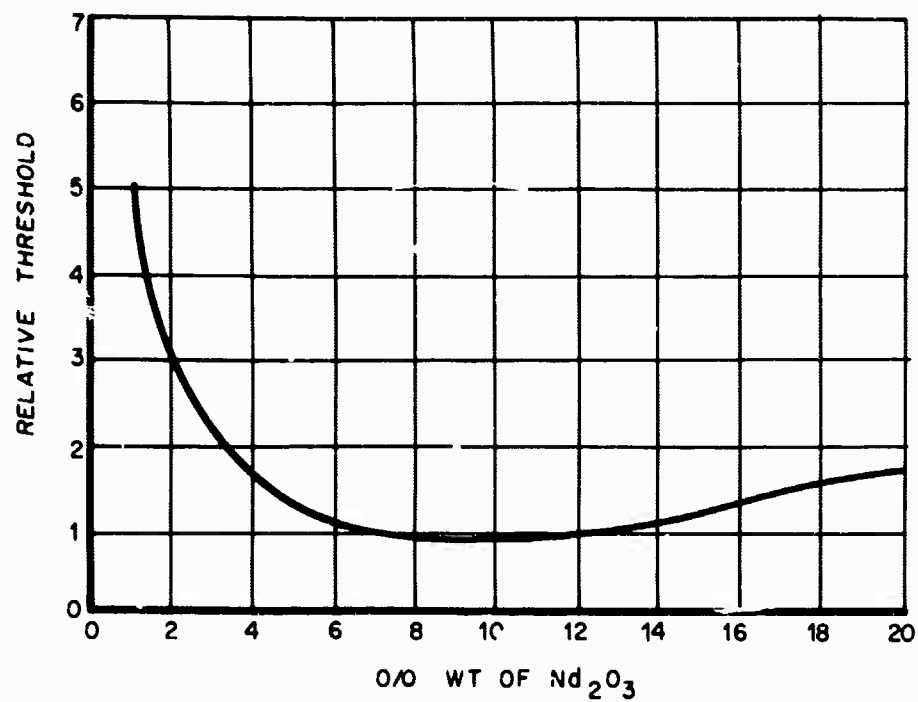


Figure B-3. Relative Threshold vs % wt of Nd_2O_3

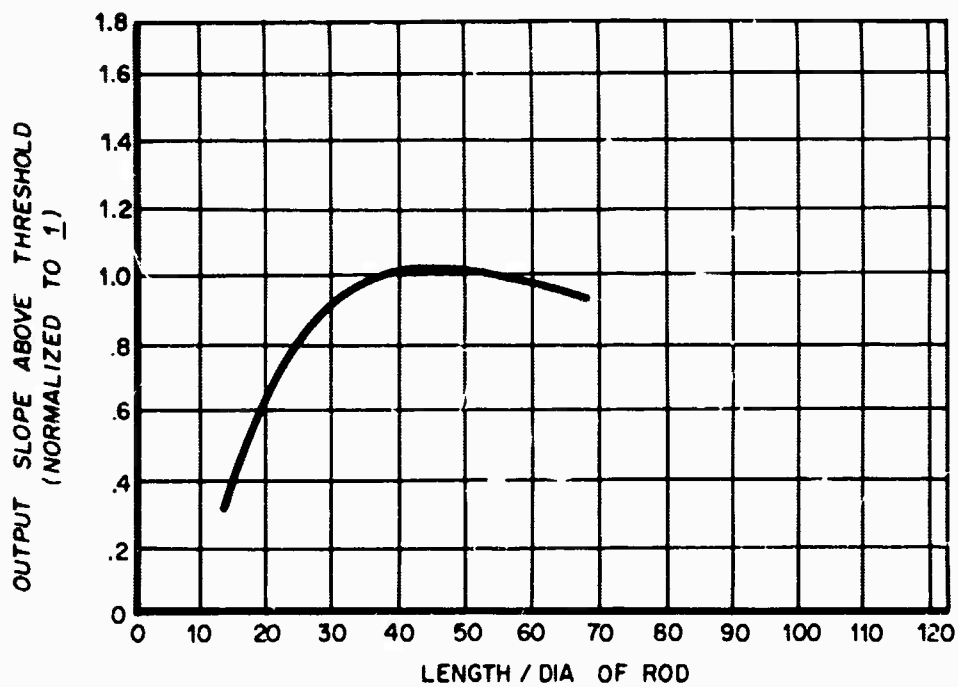


Figure B-4. Output Slope Versus Rod Length/Diameter Ratio

UNCLASSIFIED

Security Classification

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13. ABSTRACT This is the semi-annual technical report issued under Navy Contract NONr-4874(00). The period covered by this report extends from 16 June 1965 to 16 December 1965. The results of preliminary measurements performed on a neodymium doped glass rod previously used on contract NONr-3922(00) are presented. These experiments include space and time resolved measurements of pump induced birefringence during and after the pump cycle. Conclusions are drawn from the results of the theoretical and experimental investigations to date, and plans for the next period are presented.			